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SAFETY EVALUATION OF INFRARED LAMP POWER OUTPUT FOR OCULOMETER EYE/HEAD TRACKER SYSTEM

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13. ABSTRACT (Maximum 200 words)

The Air Force is concerned about the possible long-term effects of radiation used to illuminate the eye for eye tracking purposes. Toward this purpose, measurements were taken to determine the power output of the halogen lamp from the oculometer of the Honeywell (Type YG1784A01) head and eye tracker used at the Air Force Human Resources Laboratory, Operations Training Division (AFHRL/OT), Williams AFB, Arizona. Radiation from the lamp (General Electric Lamp No. 784, Emergency Lighting - Halogen) is projected through the optics of the helmet onto the user's eye. The returned or reflected signal from the pupillary region of the eye is subsequently analyzed to determine eye position. A thermopile was placed behind a small aperture at the eye position inside the helmet in order to measure the amount of radiation at the eyepoint. Output of the halogen lamp varied with input current where minimum and maximum operational currents were .8 and 1 ampere. Irradiance measurements recorded using the thermopile were .20 milliwatts/cm^2 for an .8-amp input and .55 mW/cm^2 for a 1-amp input. These readings were determined to be well within safety standards currently set by industry. However, it is suggested that ocular exposure to such radiation be minimized, as more research is required in order to ascertain chronic effects resulting from long-term exposure of the eye to low levels of radiation.

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SUMMARY

The Air Force has a considerable interest in the possible long-term negative effects encountered from the use of head and eye tracking equipment. In particular, radiation used to illuminate the eye in these devices is a topic of concern. In this report, radiation emanating from the oculometer of the Honeywell (Type YG1784A01) head and eye tracker used at the Air Force Human Resources Laboratory, Operations Training Division, Williams Air Force Base, Arizona, was measured and evaluated with respect to current industry standards.

A 6-watt halogen lamp (General Electric Lamp No. 784, Emergency Lighting) with a current variation of .8 to 1 ampere projects radiation through two filters of significant interest and off a dichroic beamsplitter on the visor of the helmet. The resulting radiation reaching the user's eye is primarily in the 1- to 2-micron band of wavelength.

Irradiance values obtained using a thermopile for .8 and 1 ampere of input were .22 mW/cm^2 and .55 mW/cm^2, respectively. Irradiance estimates were compared with permissible dosages determined by the American National Standards Institute (ANSI) and the American Conference of Governmental Industrial Hygienists (ACGIH), as well as estimates from other published research. These and other critical values were found to be at least an order of magnitude larger than the observed irradiance values. Based upon current research standards, then, the Honeywell oculometer was determined to be safe for human usage.

PREFACE

This project was performed in support of the Air Force Human Resources Laboratory, Operations Training Division (AFHRL/OT), research concerning head and eye tracking systems. This effort was managed by the University of Dayton Research Institute (UDRI), under Contract F33615-87-C-0012, Work Unit 1123-03-83, Flying Training Research Support. The UDRI work was conducted by R. J. Evans; the AFHRL/OT work, by J. C. Gainer. The laboratory technical contract monitor was Captain Paul Choudek.

This effort supports the training technology objectives as described in the present AFHRL Research and Technology Plan. The goal of the present effort was: (a) to measure the amount of radiation projected by the oculometer into the pupillary region of the eye and (b) to compare the measured radiation quantities with published standards in order to determine whether the radiation output from the oculometer is reasonably safe.

The authors wish to express thanks to Ms. Marge Keslin for final edit of the manuscript.

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SAFETY EVALUATION OF INFRARED LAMP POWER OUTPUT FOR OCULOMETER EYE/HEAD TRACKER SYSTEM

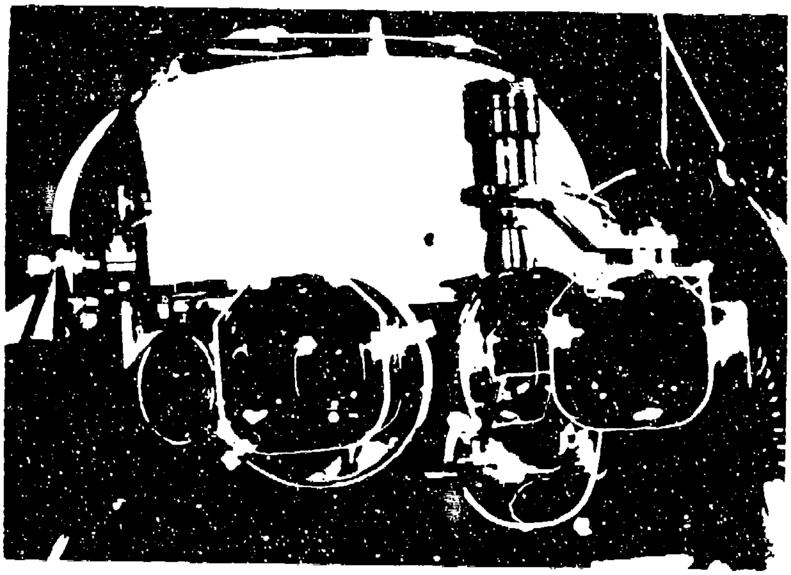
I. INTRODUCTION

Eye tracking systems may be expected to play a significant role in the future in areas such as flight simulation, target designation in military applications, and general monitoring of eye movements within psychological research. While different technologies exist for determining and measuring eye movements, one current method involves illuminating the pupillary region and surround with low levels of infrared (IR) radiation and measuring relative differences in the returned signal between the pupil and surround. Novelties involved in the use of such new technology, such as illumination of the eye for relatively long durations continued intermittently over a number of years, may present health hazards to the user of the system never encountered previously in natural, industrial, or occupational settings. Before proceeding with the development of such systems, it is important that the determination of possible health hazards be studied in detail. The purpose of this report is to measure and analyze the radiation output from one such system.

The oculometer of the Honeywell (Type YG1784A01) head- and eye-tracking system used at the Air Force Human Resources Laboratory, Operations Training Division (AFHRL/OT), at Williams AFB, Arizona, records eye movements by illuminating the pupillary area and surround. To accomplish this function, IR radiation from a halogen lamp in the helmet is projected into the eye. The reflections from the cornea and areas around the pupil are recorded to predict the eye's position. A six-watt halogen lamp (GE No. 784 - emergency lighting type) with an approximate color temperature of 3175°K is the source of the infrared radiation. The radiation is projected through two filters and reflected off of a dichroic beamsplitter located on the visor of the helmet. The remaining sections address the optics of the oculometer, the equipment used in the measurements, results from the measurements, possible regions of damage within the eye, and comparison of results with published standards.

Honeywell Oculometer Optics

The oculometer of the Honeywell head- and eye-tracking helmet used for evaluation contains three filters of significant interest. Figure 1 provides a diagram of their positioning on the helmet. Figure 2 provides a graph of their spectral filtering properties. The filter adjacent to the halogen lamp is a Schott RG850 filter. This filter acts as a band-pass between approximately .8 and 2.8 microns (see Figure 2). The Kodak Wratten (No. 87) filter follows the Schott filter in the system. Transmission characteristics of this filter are low-pass, dropping from approximately 87% transmission at 1.1 microns to



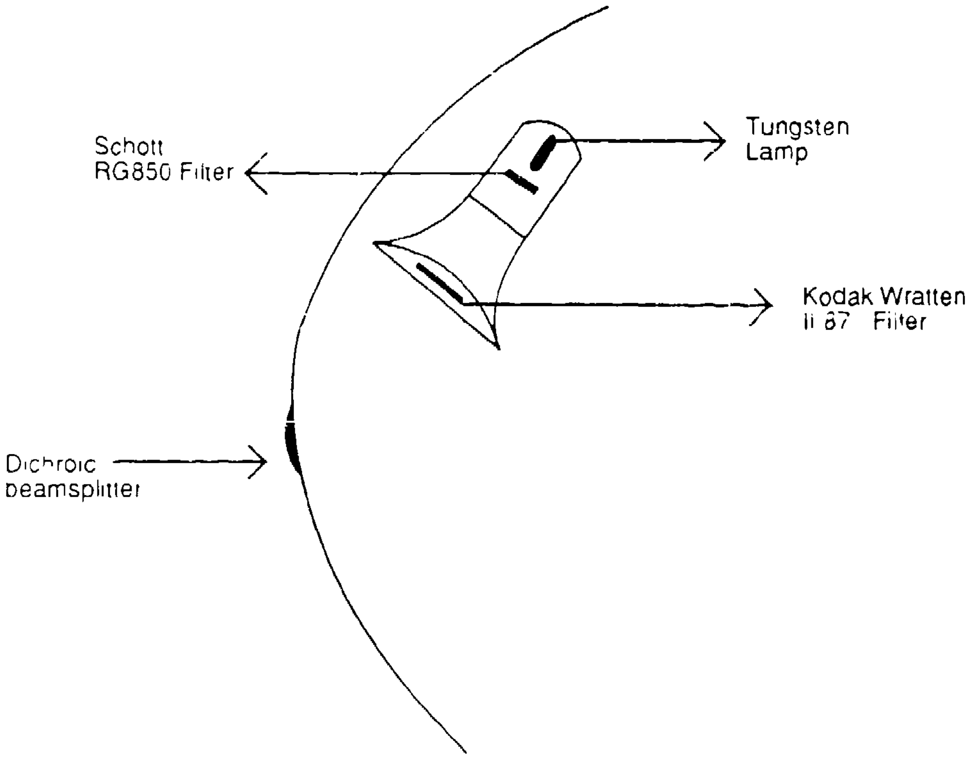


Figure 1. Optical Assembly.
Helmet and filter system.

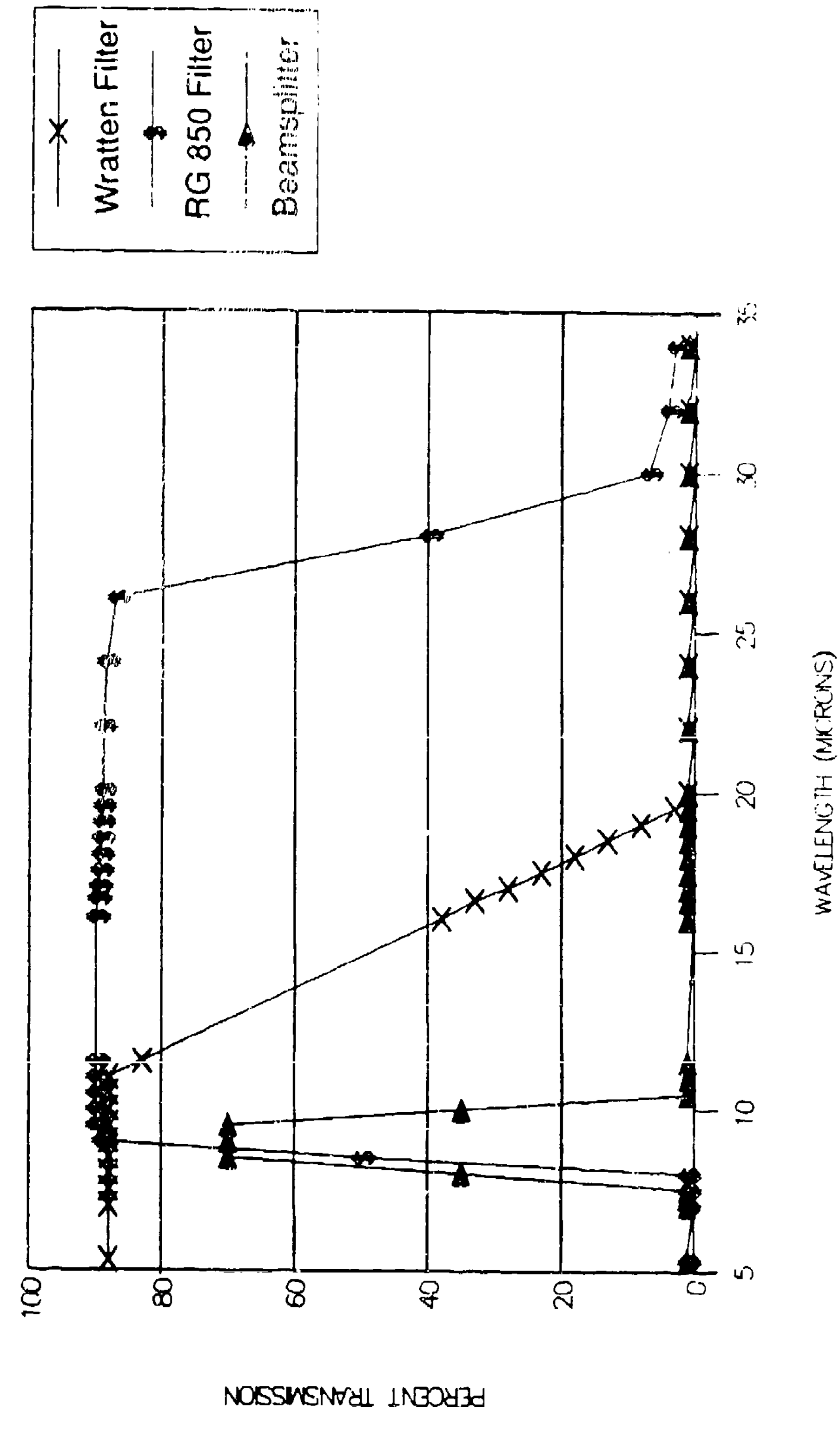


Figure 2. Filter Transmittance.

zero transmission at 2 microns. The dichroic beamsplitter located on the spherical surface of the helmet's visor (see Figure 1) completes the optical system filtering design. The purpose of this component is to reflect the IR radiation transmitted through the first two filters into the eye while passing the visible radiation out the front of the visor. Transmission characteristics for this optical component (see Figure 2) are band-pass between .8 and 1 microns. The transmission characteristics of the first two components, the Wratten filter and the RG850 filter, denote radiation passed through the optics to the eye. The transmission characteristics of the beamsplitter, though, denote radiation passed out the front of the visor; i.e., radiation outside the .8 to 1 micron spectral band-pass is the radiation reflected to the eye. Figure 3 estimates the combined transmittance of the three filters and indicates that most of the radiation passed to the eye would be between 1 and 2 microns. Along with the overall transmission of the three filters, Figure 3 also contains the radiant emittance from a black body of 3175°K, denoted as an approximate color temperature for the halogen lamp.

Equipment

The equipment used in the measurement process consisted of:

(1) A Newport Research Corporation (NRC) Model VPH-2 Thermopile (Model No. 360001, Serial No. 1133; flat response between .3-20 microns)

(2) A Kepco Power Supply (Serial No. 020969)

(3) A Scientech 362 Power Energy Meter

(4) A Fluke 77 Multimeter

(5) A Find-A-Scope S-1 Photocathode

A pictorial of the equipment setup is shown in Figure 4. Leads from the thermopile were connected to the Scientech Meter to record power output measured by the thermopile. The Kepco Power Supply was connected in serial with the multimeter and the halogen lamp from the head and eye tracker. Current from the power supply was varied indirectly through the DC voltage control on the power supply. The power supply also contained a control for limiting the current output. The multimeter was used to measure the current input to the halogen lamp.

The head- and eye-tracker helmet was placed in an upside-down position on a table while the thermopile was held in place at the eye viewpoint inside the helmet by clamps. An aperture was placed directly in front of the thermopile to limit and define the area of irradiation. Black cardboard was placed around the

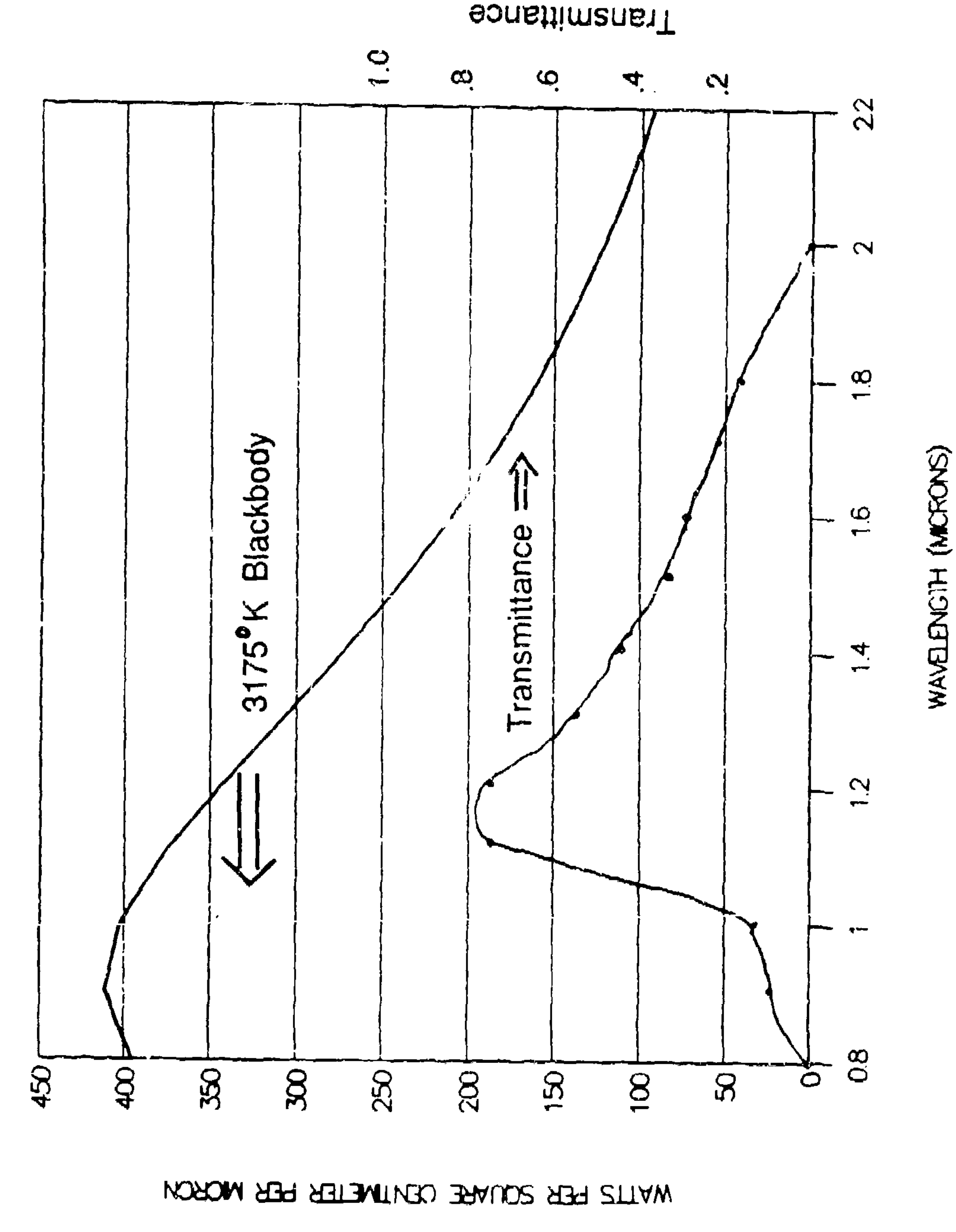


Figure 3. Combined Filter Transmittance.

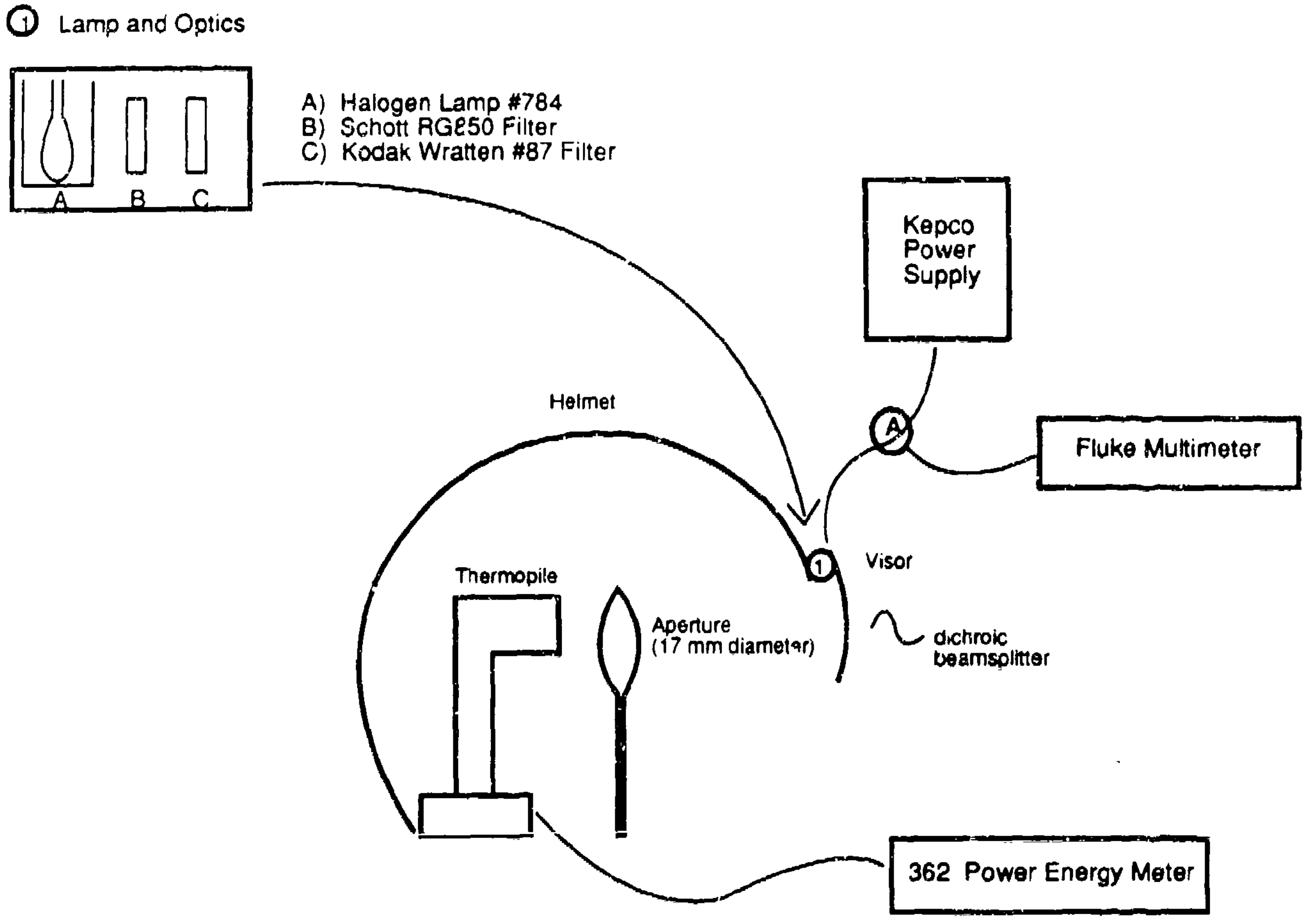


Figure 4. Equipment Setup.

helmet to control variation in the thermal background. The Find-A-Scope photocathode was used to verify that the majority of the beam radiating from the halogen lamp to the eyepoint was passing through the aperture into the thermopile.

Irradiance was measured for current inputs of .8 and 1 amperes with the IR source covered in one instance to provide a background reading and uncovered in a second instance to provide a signal-plus-background reading. Results are provided in Table 1. For a .8-amp input, the energy meter recording was approximately 4.0 mW with the IR source covered and 4.5 mW with the source uncovered. For a 1-amp input, the meter reading was approximately 4.1 mW with the IR source covered and 5.5 mW with the source uncovered. The aperture was 18 mm in diameter providing an aperture area, A_a, of approximately 2.54 cm^2. Irradiance due to the IR source was then computed by subtracting background power from signal-plus-background power and dividing the result by the aperture area. For .8 and 1 ampere inputs to

the halogen lamp, the resulting irradiance at the eyepoint due to the halogen lamp was computed as .20 mW/cm^2 and .55 mW/cm^2, respectively. As a basis of comparison, consider a 75-watt bulb viewed from six feet away. The surface area covered by a sphere with a six-foot radius would be $4\pi r^2$ or 452.4 ft^2 yielding an irradiance value of .178 mW/cm^2 from a viewing distance of six feet. A significant portion of the radiation from the 75-watt bulb, though, is distributed in the visible wavelengths between .4 and .8 microns. The spectral shift into the visible region for the light bulb would make the bulb a more likely source of ocular damage as will be discussed later in the report. Again, due to the spectral shift in energy, the discomfort resulting from staring at the 75-watt bulb would be much greater than discomfort attributed to the IR radiation. Only the thermal or heating effects felt from the 75-watt bulb (which are not noticeable) would be analogous to those felt from the IR radiation.

More along the lines of natural sources of radiation, Smedley (1980) estimated the amount of retinal irradiance (using 50% as the percentage of attenuation by the ocular media prior to the retina) one might receive from looking at the ground on a bright, sunlit day. This estimated value was 24 $microwatts/cm^2$ (.024 mW/cm^2), and Smedley suggested that it might be reasonable to employ this value as a limit for a daily eye safety standard. Sliney and Freasier (1973) suggested the corneal dose rate from sunlight to be about 1 mW/cm^2. This value is reasonable when compared with Smedley's estimate if we neglect ground reflectance and ocular attenuation from Smedley's estimate. Other estimates of sky irradiance sampled throughout the day (Sliney & Marshall, 1980) are: (1) California, summer sun near zenith = 115 mW/cm^2 and (2) California near sunset = 18 mW/cm^2.

These estimates of the irradiance from natural sunlight act as upper and lower bounds on the oculometer radiation ranging from Smedley's estimate (.024 mW/cm^2) obtained from the ground's reflection to 115 mW/cm^2 which is an average of the sky irradiance at the sun's zenith. However, the spectral distribution of energy contained in the sun's rays is more harmful to the human eye than the IR radiation from the oculometer.

Measurements of irradiance provided in this report are in units of power per unit area (e.g., milliwatts per square centimeter). In many instances, however, this quantity is divided by the solid angle the source subtends relative to a measurement point. This quantity is then provided in power per unit area per unit solid angle (steradian). In Appendix A, this topic is discussed in more detail and computations for these quantities are provided in Table 1.

Table 1. Irradiance Measurements

	Current Input to Halogen Lamp (amperes)			
	.8		1.0	
	Background	Signal+Background	Background	Signal+Background
Power (mW)	4.0	4.5	4.1	5.5
Aperture area (cm^2)	2.54	2.54	2.54	2.54
Irradiance (mW/cm^2)	1.57	1.77	1.61	2.16
Difference (S+N - N)	0.2 mW/cm^2		.55 mW/cm^2	
Retinal (solid angle) irradiance	1.54 $mW/(cm^2\ sr)$		4.23 $mW/(cm^2\ sr)$	

In order to actually validate the output from the thermopile and power meter, a calibrated source was applied to the existing setup within the helmet. A one-milliwatt laser source was projected through the aperture of the setup in Figure 4. The power meter reading of approximately five milliwatts was indicative of the signal-plus-noise reading (signal of one milliwatt, background of four milliwatts) that was expected.

II. DISCUSSION

Loci and Onset of Ocular Damage

The irradiance quantities derived from the measurements must be compared with relevant standards in order to reach a meaningful conclusion. As previous research shows (e.g., Moffitt, 1980), there is ambiguity concerning the type of damage most likely to occur and the nature of comparison necessary. Time of exposure, place of damage (corneal, lenticular, retinal), and type of damage (e.g., thermal, photochemical) are the major dimensions of interest. In addition to these factors, radiation from an oculometer represents a very unique situation. While the instantaneous dose of radiation generated by the oculometer is quite small, it is applied for a relatively long period of time with each use and may be employed on a recurring basis over a number of years. An overwhelming amount of experimental data exists which records immediate (within hours) ocular damage as a

function of short-term (on the order of seconds) radiation exposure. Long-term exposure to radiation, however, is less amenable to experimental research methods. Most of the information in this area is based upon observational or survey studies. For example, Dunn (1950) collected information on glass blowers subjected to 140 mW/cm^2 for a number of years and found no evidence of extraordinary cataract formation. Sliney and Freasier (1973), however, did find evidence of lenticular cataract formation in glass workers subjected to 40-80 mW/cm^2 for 10-15 years. From this work, they suggested that a chronic level exposure limit to IR radiation be set at 10 mW/cm^2. Research suggests that the long-term effect of introducing low levels of radiation into the eye enhances the onset of aging processes to the eye, such as opacities in the lens and cornea (Pitts, Cameron, Jose, Lerman, Moss, Varma, Zigler, Zigman, & Zuclich, 1986). For example, loss of vitamin C and protein in the lens as a function of the aging process results in lenticular opacities. Wolbarsht (1980) noted decreases in protein level in the lens as a function of exposure to IR radiation and concluded that IR exposure may be considered to be an acceleration of the aging process. It should be noted, though, that exposure levels in Wolbarsht's work were approximately two orders of magnitude larger than those measured in this report. Exposure times, though, were less than 1000 seconds.

Effects from small changes in nutrients such as protein level may be cumulative across various radiation sources and over time. Such combinatorial possibilities resulting in chronic ocular radiation damage over years of application will make it quite difficult to establish well-defined guidelines for exposure.

In the human eye, the major areas of concern with respect to possible damage are the cornea, iris, lens, and retina. Figure 5 provides a good indication of where these media lie in the ocular pathway. In addition to these media, the aqueous and vitreous humours will absorb a significant amount of radiation. In Figure 5, note how the iris covers much of the lens from outside radiation. While there is little concern about thermal damage to the iris relative to the cornea or lens, dissipation of heat from the iris to the lens has been suggested as a mechanism for thermal damage to the lens.

Spectral absorption curves for the cornea, aqueous humour, lens, vitreous humour, and retina are presented in Figure 6 (Sliney & Wolbarsht, 1980). In addition, the total transmission of the cornea, aqueous humour, lens, and vitreous humour is presented in Figure 7 along with a retinal absorption curve (Sliney & Freasier, 1973). The tungsten bulb (GE Lamp No. 784) used in the oculometer is characterized in the spectral domain as a 3175° Kelvin blackbody.

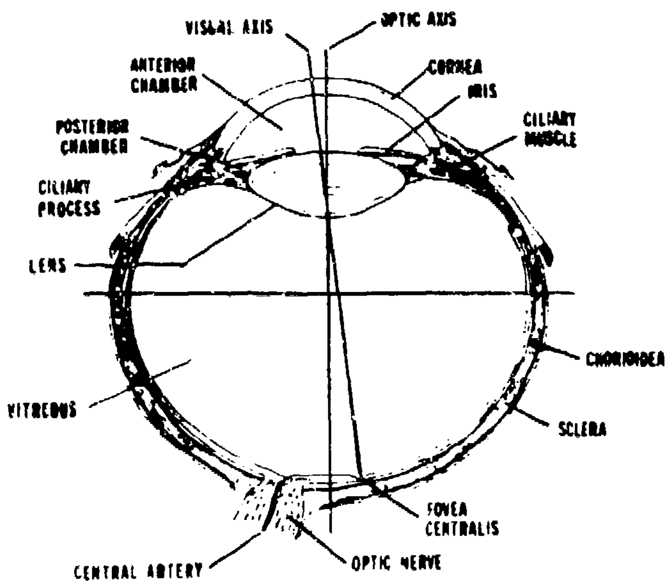


Figure 5. Schematic Diagram of the Eye.

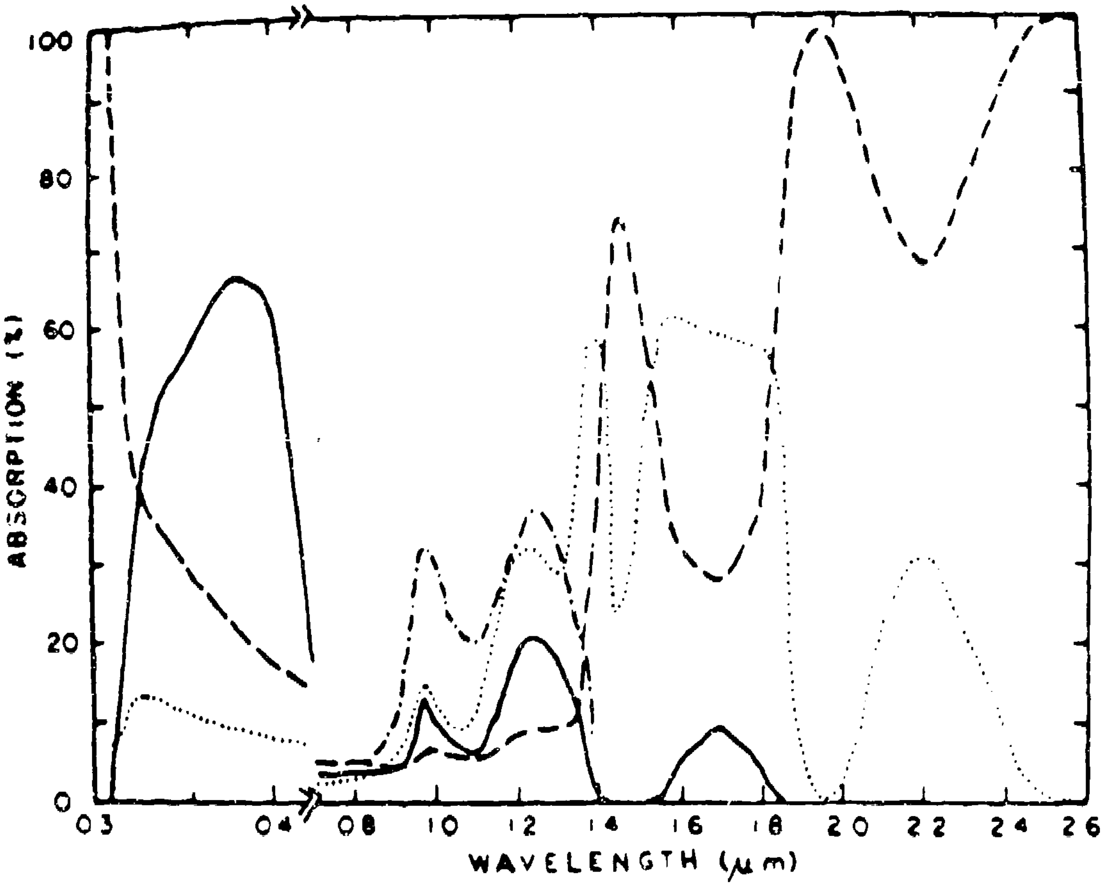


Figure 6. Absorption Curves for Ocular Media: broken curve, cornea; dotted curve, aqueous humour; full curve, lens; chain curve, vitreous humour (Sliney & Wolbarsht, 1980).

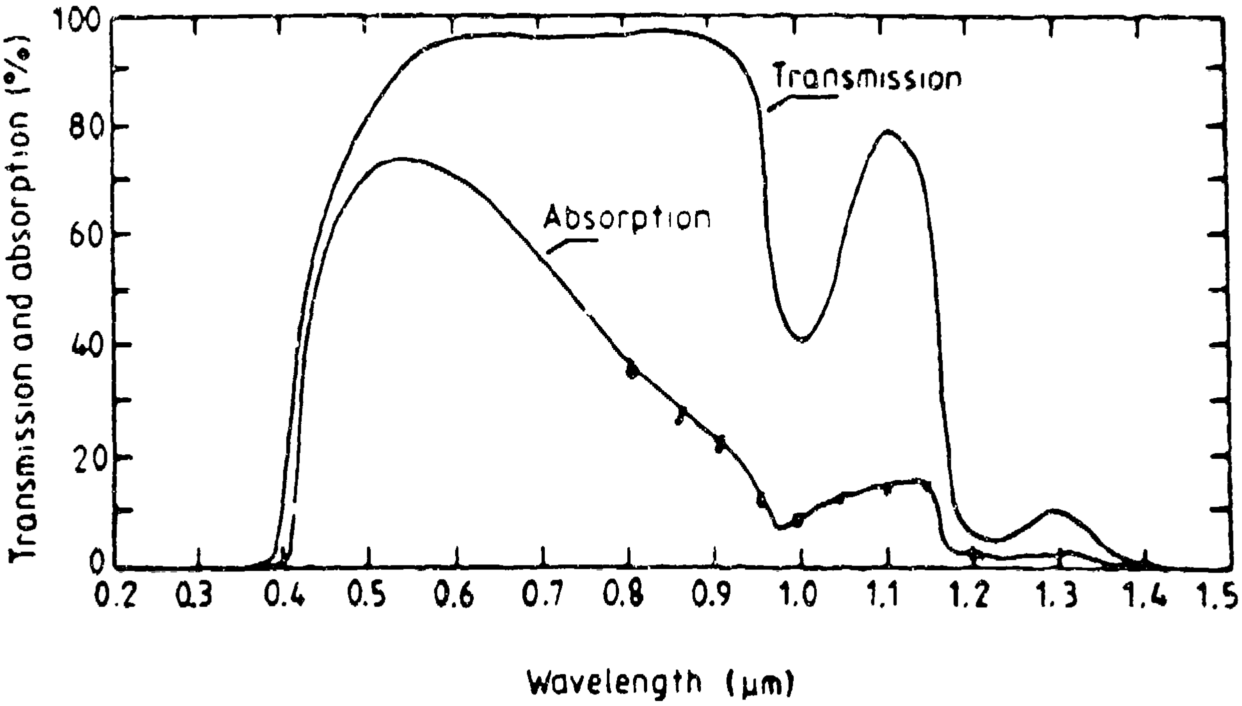


Figure 7. Absorption and Transmission Curves at the Retina. Total spectral transmission of human cornea, aqueous humour, lens, and vitreous humour, together with the spectral absorption within the human retina (Sliney & Freasier, 1973).

Figure 8 denotes this distribution of irradiance over wavelength. By using this distribution as input to the filters denoted in Figures 3 (oculometer transmittance) and Figure 6, the approximate spectral irradiance distributions for the cornea, lens, and retina are shown in Figure 9. In Figure 9, the y-axis contains a multiplication factor which equates total irradiance (i.e., spectral radiance integrated over wavelength) with the values obtained in the measurements described in this report. For corneal irradiances of .2 and .55 mW/cm^2, the multiplication factors for the y-axis are approximately 1.66×10^{-6} and 4.55×10^{-6}, respectively. The highest point on the curve in Figure 8 is approximately .46 and 1.25 $mW/(cm^2$ micron), respectively, for the two corneal irradiances.

Referring to Figure 9, note that while oculometer filters transmit a majority of the energy between 1 and 1.5 microns (denoted by corneal spectral radiance in Figure 9), the cornea (and aqueous humour) tends to absorb about 50% of the energy in this band, allowing only about 50% of the corneal irradiance to reach the lens. Approximately another 10% is filtered by the lens and the vitreous humour, allowing only about 40% of the corneal irradiance to reach the retina. Note the ocular attenuation is necessarily spectrally dependent. Given a different source of illumination, the amount of energy transmitted through the ocular media may vary greatly depending upon

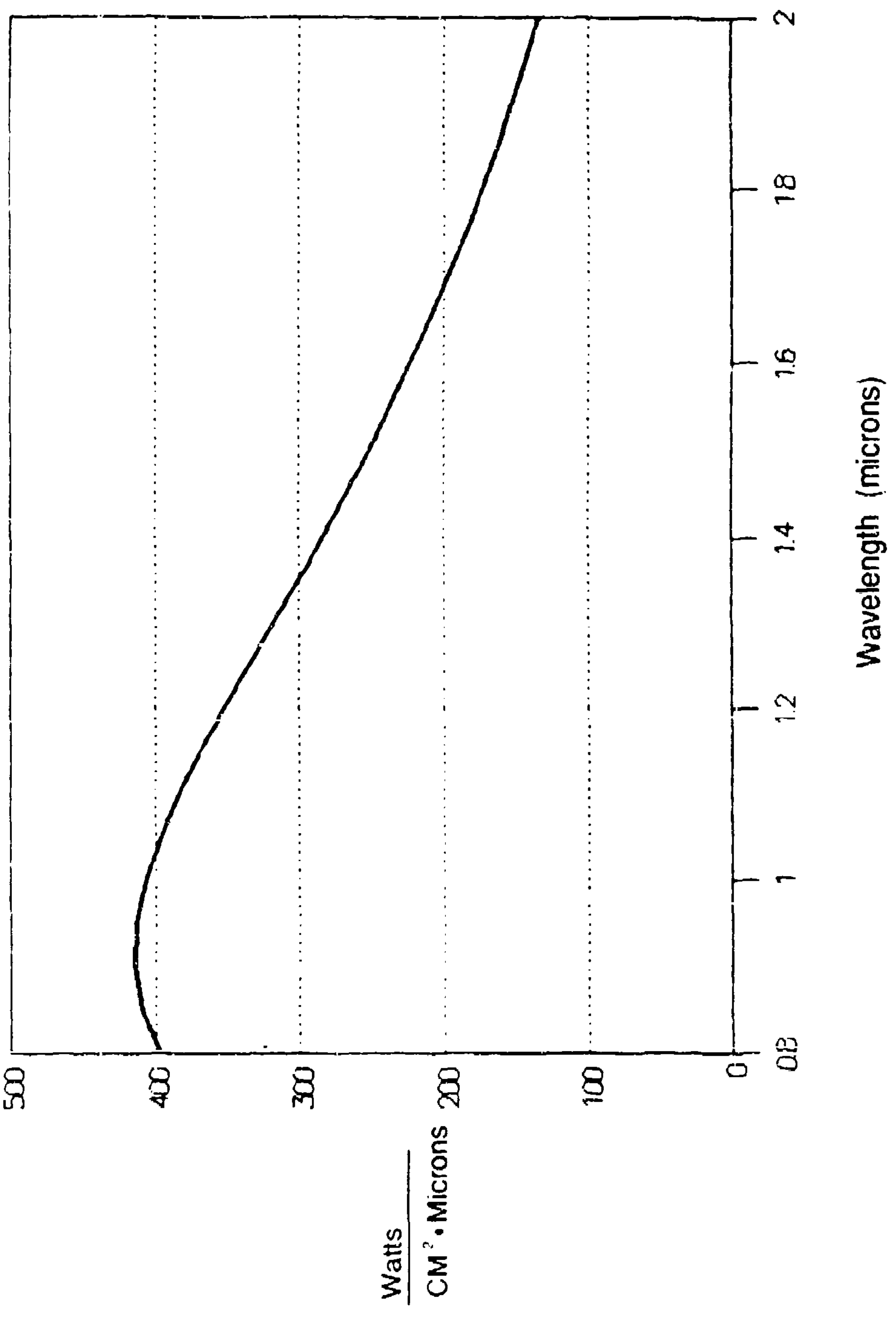


Figure 8. Spectral Blackbody Radiation at 3175°K.

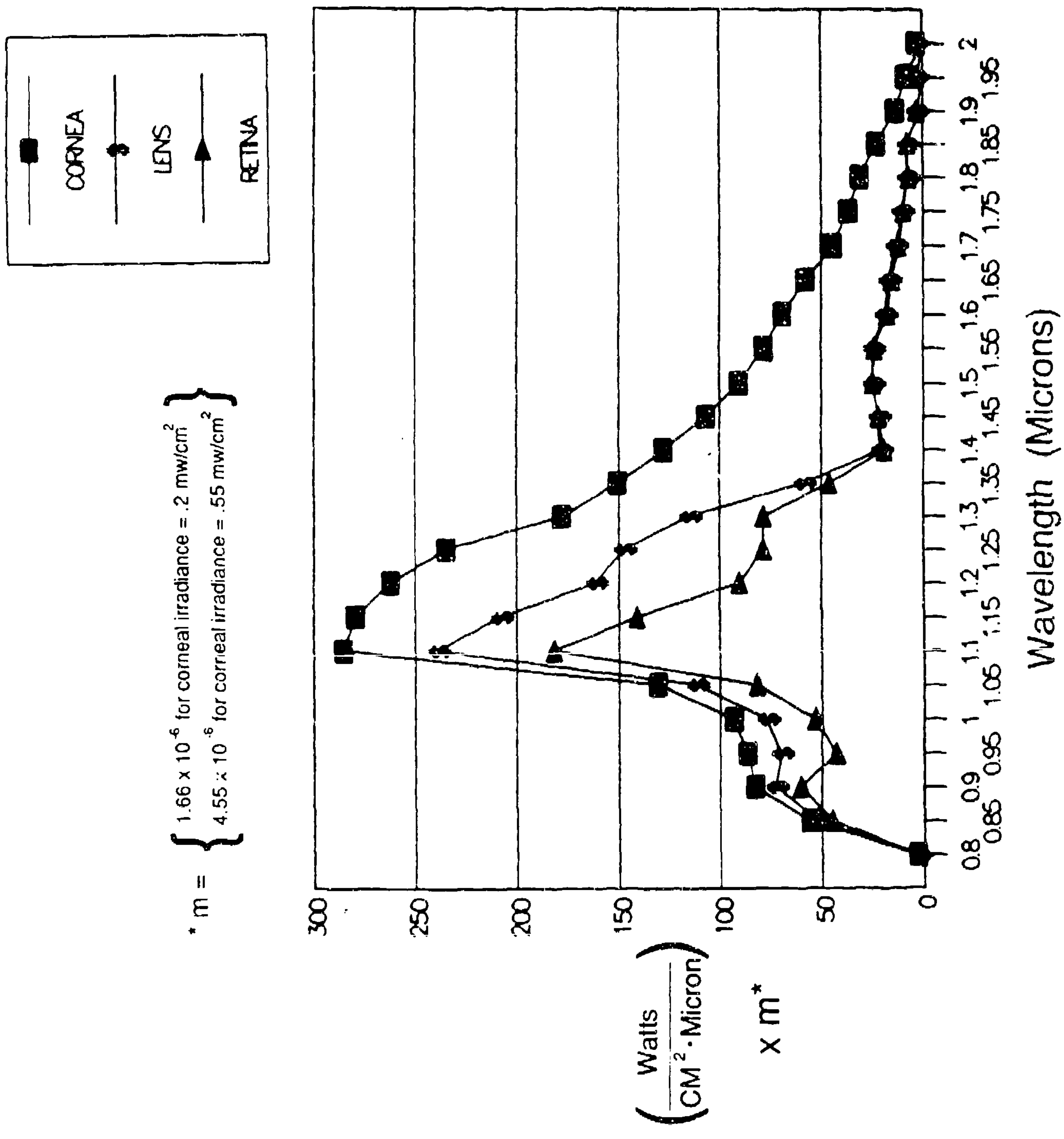


Figure 9. Approximate Spectral Radiance for Cornea, Lens, and Retina.

the spectral distribution of the source. In addition, while one would expect ocular attenuation of 50% or more of the radiation incident on the cornea to the radiation reaching the retina, a word of caution is in order. The lens will redistribute the energy incident upon it according to current focal conditions or where the user is focusing. The redistribution, then, can possibly focus the energy on the retina in a much denser fashion than previously indicated.

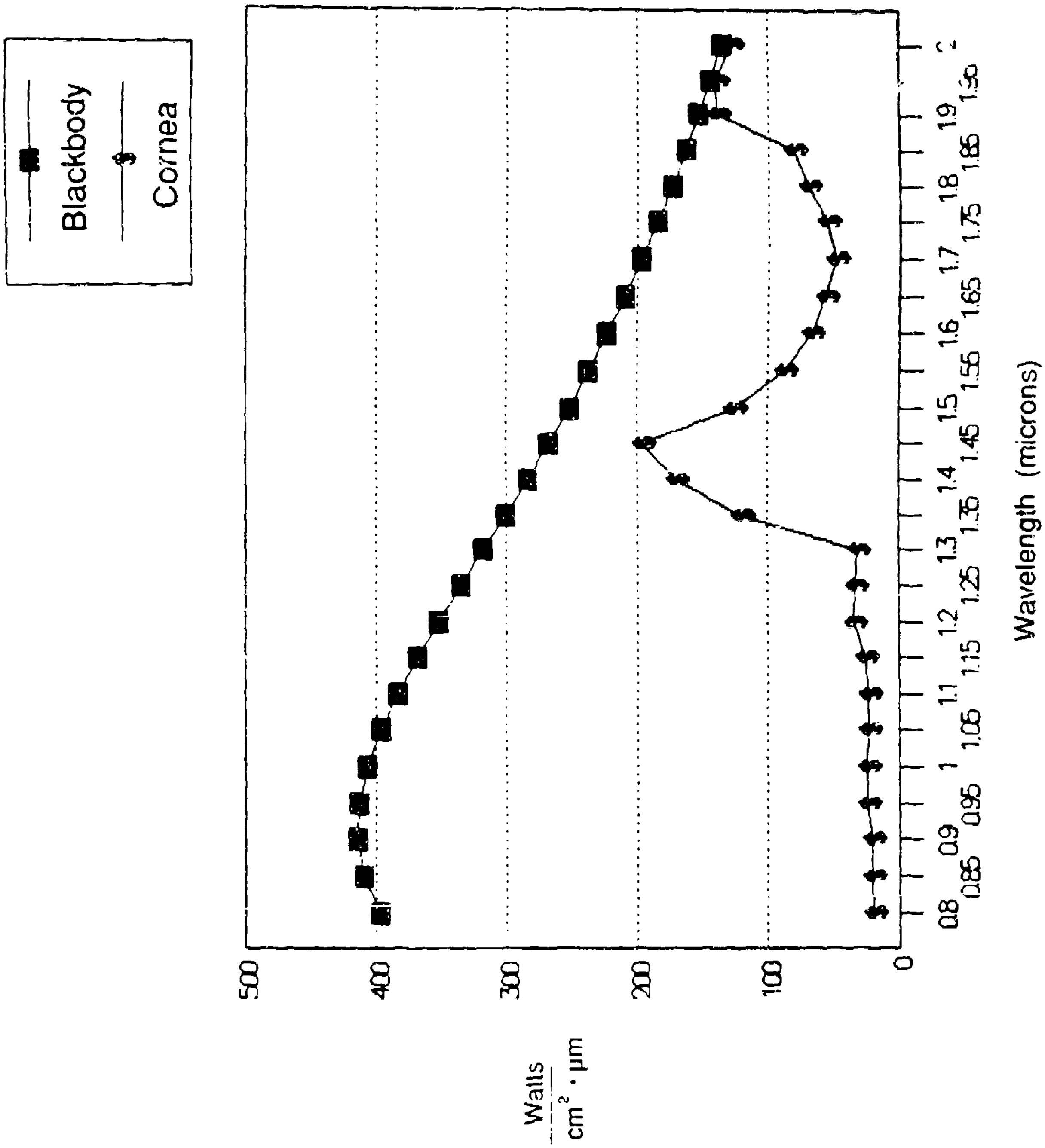
The lens has been noted as a primary location for thermal damage to occur because it receives no blood flow to dissipate heat or repair itself. In addition, lenticular opacification or cataract formation can be quite damaging to overall vision while such opacification in other tissue may have no effect on the functioning of the particular tissue or media.

Transparency of the cornea may also be affected by IR radiation. However, the ability of the cornea to repair its outer layers, and the fact that the cornea will absorb less than 20% (see Figure 10) of the tungsten bulb incident upon it, makes it a much less likely source of radiation damage than the lens.

In the retina, the most likely types of damage in this instance consist of thermal and photochemical damage (Ham, Mueller, Ruffolo, & Clarke; 1979). However, Ham et al showed that short wavelengths in the visible spectrum (e.g., .4 microns) were overwhelmingly responsible for photochemical damage. Doses of radiation in the IR spectrum would cause significant thermal damage to the retina prior to the introduction of any photochemical damage. Additionally, the task of the Honeywell head and eye tracker used at AFHRL/OT is such that duration of use would range up to an hour. This represents a long period of exposure relative to the introduction of most artificial sources directly into the eye. Because the retina is well vasculated, the trade-off between amount of irradiation and time of irradiation is not linear. A small amount of heat on the retina generated by low levels of radiation from the oculometer may be easily dissipated by the blood supply to the retina.

Standards for Exposure Limits

Two traditional standards exist governing maximum permissible exposure. These standards were constructed by the American Conference of Governmental Industrial Hygienists (ACGIH) and the American National Standards Institute (ANSI). While the ANSI standards were devised for laser radiation, they may also be used as a conservative estimate for broadband sources of radiation. The ACGIH standards use a weighting scheme (see Table 2 taken from Chapter 11 of Moseley, 1988) to determine the possible damage due to blue light and thermal radiation at various wavelengths.



<u>Figure 10.</u> 3175°K Blackbody Radiance and Absorption by Correa.

From Table 1, recall that the maximum observed irradiance is .55 mW/cm^2 for a 1-ampere input. Calculations for the ANSI standard are provided in Appendix A. These calculations resulted in an exposure upper limit of 5.25 mW/cm^2. The experimentally obtained ocular irradiance of .55 mW/cm^2 is an order of magnitude less than the ANSI standard calculated in Appendix A.

ACGIH standards provide irradiation limits for: (a) retinal burns from all infrared sources in the A (.76-1.4 microns) and B (1.4-3 microns) regions, (b) retinal burns from infrared sources with no bright visible component, and (c) lenticular burns from all infrared sources. Derivations for estimates from these computations are provided in Appendix B. In addition, as mentioned, the ACGIH standards weight the observed irradiation according to the effectiveness of the spectral bands. Appendix B provides a conservative estimate for the weighting of the observed irradiance, .55 mW/cm^2, according to the thermal hazard coefficients from Table 2.

A conservative estimate of effective irradiation, as calculated from Appendix B, was .55 mW/cm^2 (or the equivalent of the actual irradiation). ACGIH standards given in Appendix B for (a), (b), and (c) as explained above were: (a) 10 mW/cm^2, (b) 600 mW/cm^2, and (c) 10 mW/cm^2. Each of these standards is at least an order of magnitude larger than the conservative estimate of effective irradiation, .55 mW/cm^2.

Estimates provided by other researchers may also be of interest when compared to the ANSI and ACGIH standards. For example, Ham et al (1979) found that radiant exposure in the .7-1.4 micron spectrum required the equivalent of 611 watts/(cm^2 sr) for a 1000-second duration to produce minor thermal lesions in the eye of a rhesus monkey. While this value is quite high, note that it does not represent a permissible dosage but the dosage required to produce a lesion. Data provided from a study by the Siemans Corporation (Siemans, 1979) yielded a conservative estimate of 380 mW/(cm^2 sr) as a permissible upper limit. All of the critical values noted are at least an order of magnitude greater than the observed estimates even when a small solid angle (e.g., Ω=.01 sr) is substituted for the conservative estimate used above of Ω=1.94 steradians.

The irradiance values measured from the Honeywell head and eye tracker were typically more than an order of magnitude less than the critical values noted in this paper as well as being less than the estimated IR output of other head- and eye-tracking configurations (Moffitt, 1980; Marshall & Wood, 1985). Marshall and Wood, for example, used an optometer with an upper wavelength cut-off of .85 microns. They estimated irradiance to be .2 mW/cm^2 at the eyepoint inside the helmet. Using an upper wavelength cutoff of 1.4 microns and assuming the spectral

Table 2. Blue Light and Thermal Hazard Spectral Weights

Wavelength (nm)	Blue-light hazard function, *B*,	Thermal hazard function, *R*,
400	0.10	1.0
405	0.20	2.0
410	0.40	4.0
415	0.80	8.0
420	0.90	9.0
425	0.95	9.5
430	0.98	9.8
435	1.0	10
440	1.0	10
445	0.97	9.7
450	0.94	9.4
455	0.90	9.0
460	0.80	8.0
465	0.70	7.0
470	0.62	6.2
475	0.55	5.5
480	0.45	4.5
485	0.40	4.0
490	0.22	2.2
495	0.16	1.6
500–600	$10^{[(450 - \lambda)/50]}$	1.0
600–700	0.001	1.0
700–1049	0.001	$10^{[(700-\lambda)/500]}$
1050–1400	0.001	0.2

Note. Spectral weighting functions for assessing retinal risks from broadband optical sources proposed by ACGIH (1981).

irradiance curve to be flat throughout the entire spectrum, they estimated the overall irradiance to be approximately 1 mW/cm^2.

A final point of concern still lies with the frequency of usage of an oculometer over long periods. The only comparable data for such usage was the observational data cited earlier in this report for glass blowers and steel workers. Currently, oculometer usage is such that a reasonable upper limit would be 300 hours of usage over a five-year period which is equivalent to about an hour of usage per week for a five-year period. Given the levels of oculometer irradiation provided in this report (.55 mW/cm^2), this dose may be assumed to be harmless because: (1) it is only an order of magnitude larger than doses cited for reflected sunlight off the ground of about .048 mW/cm^2 (Smedley,

1980; uncorrected for ocular attenuation of 50%) and (2) it reflects an order of magnitude less irradiation as well as much less temporal exposure to the observational data gathered from glass blowers and steel workers (Dunn, 1950; Sliney & Freasier, 1973) where evidence on cataract formation has been relatively inconclusive.

III. CONCLUSIONS

The maximum corneal irradiance projected from the Honeywell oculometer was determined to be .55 mW/cm^2. This value was well below an ANSI calculated standard of 5.5 mW/cm^2 or the most conservative ACGIH standard of 10 mW/cm^2. Under these premises, then, the Honeywell oculometer may be determined safe for usage.

Irradiation generated by an oculometer, however, is a novel source of ocular irradiation and its time duration and extent of usage is probably not well matched by the studies used for determining ANSI or ACGIH standards. Here, though, typical dosages of sunlight and thermal irradiation from occupational work such as glass blowing or mill work appear more applicable. Even these radiation sources, though, cannot be considered equivalent to the oculometer application due to the spectral distribution and amount of power.

Surveys from long-term occupational exposure to thermal radiation show an increased risk for senile lens opacities (Pitts et al, 1986). However, the irradiances are typically between 40 and 140 mW/cm^2 which are approximately two orders of magnitude greater than the oculometer exposure. Measurements of ocular irradiation from sunlight are more in line with the ocular irradiation reported here (i.e., .048 to 110 mW/cm^2 corneal irradiation). However, the sun's energy is distributed more in the visible wavelengths than the radiation from the oculometer. Given the danger from shorter wavelengths is greater than that of longer wavelengths, the danger from the oculometer should be no greater than that of natural sunlight. However, as Pitts et al report from cultural observations, the occurrence of cataracts does increase as a function of exposure to sunlight over both time and amount of irradiation.

It is clear, then, that irradiation from an oculometer for brief periods is relatively harmless in the sense that indirect sunlight is harmless. However, continual long-term use of an oculometer must still be regarded with caution because of its potential contribution to long-term opacities in the ocular media.

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APPENDIX A: SOLID ANGLE COMPUTATION

SOLID ANGLE COMPUTATION

In some instances, there is ambiguity concerning the dimensions and locale of the actual radiation measurements. For example, the values provided in the report thus far denote irradiation at the cornea or entrance to the eye in watts/cm^2. In some instances, these dimensions are converted into irradiance per unit solid angle or watts/(cm^2 steradian). This is accomplished by dividing irradiance in watts/cm^2 by the solid angle subtended by the source (e.g., a bulb) or an aperture through which the source illuminates (e.g., the pupil) the area of interest. Computation of the solid angle is arrived at by dividing the area the source or aperture covers by the square of the distance from the source or aperture to the point of interest. For example, irradiance at the entrance to the eye (corneal irradiance) in watt/cm^2 may be converted into retinal irradiance in watts/(cm^2 sr) by dividing entrance irradiance by the solid angle the pupil subtends measured from the retina. This solid angle, defined in steradians, is found by dividing the area of the pupil (38.50 mm^2 as defined by ANSI, 1973) by the square of the approximate distance from the pupil to the retina (289 mm^2). The result is a solid angle of .13 steradians. Dividing the eyepoint irradiance computed above by this solid angle yields a retinal irradiation of 1.54 and 4.23 mW/(cm^2 sr), respectively, for .8 and 1 amperes input. Tabular results are presented in Table 1. Note that retinal irradiance in this instance gives the amount of irradiation at the cornea per unit solid angle relative to the retina. The attenuation taking place between the cornea and the retina is not accounted for in this measurement. The term, "retinal irradiance," may indeed be somewhat misleading. As Smedley (1980) suggests, it is more appropriate to multiply corneal irradiance by the overall transmittance of the ocular media between the cornea and the retina in order to provide an estimate of retinal irradiance.

APPENDIX B: ANSI OCULAR RADIATION EXPOSURE LIMITS

ANSI OCULAR RADIATION EXPOSURE LIMITS

ANSI Standard Z13.1-1980 (P32) provides recommendations on the maximum permissible exposure for <u>direct viewing</u> of laser sources. For time periods less than an eight-hour work day, the upper limit on the maximum permissible exposure for a diffuse reflection of a laser beam of wavelength τ, .7 microns < τ < 1.4 microns, directed at the eye is defined by:

$$H = 320 \text{ X } (10)^{2(\tau-.7)} \text{ X } 10^{-} \quad (\text{Watts/cm}^2) \quad .7 < \tau < 1.05\ \mu m$$
$$= .001 \quad (\text{Watts/cm}^2) \quad 1.05 < \tau < 1.4\ \mu m.$$

H is the maximum permissible exposure and τ is the wavelength in microns (e.g., .8 microns would be entered as .8) of the laser. The equation employed above is conservative or provides a low estimate of the critical value due to a number of reasons. First, the equation chosen above is an ANSI standard for a wavelength in the .7-1.4 micron range. Standards for wavelengths greater than 1.4 micron allow a higher critical dosage. Next, the radiation reflected from the halogen lamp is diffuse compared to the reflection from a laser source. Finally, the choice of .8< τ < 1.4 microns for insertion into the equation above adds to the conservative estimate of the critical irradiance. As Figure 9 shows, approximately 15-20% of the irradiance is distributed above τ > 1.4 microns.

There are a number of ways to use the equation above to arrive at a value for H, the critical irradiance. We shall begin with the assumption that approximately 50% of the spectral irradiance is located between .8 and 1.05 microns and that the other 50% is located between 1.05 and 1.4 microns. For the irradiation located between .8 and 1.04 microns, a single value of τ = .8 is chosen for the critical irradiance equation. The critical irradiance equation now evaluates to:

$$H = .5 \text{ X } 320 \text{ X } 10^{2(.8-.7)} \text{ X } 10^{-} + .5 \text{ X } .001$$
$$= .00525 \quad (\text{Watts/cm}^2)$$
$$= 5.25 \quad (\text{mW/cm}^2).$$

APPENDIX C: ACGIH OCULAR RADIATION EXPOSURE LIMITS

ACGIH OCULAR RADIATION EXPOSURE LIMITS

The ACGIH method for determining ocular radiation exposure limits is based upon a method which spectrally weights irradiance according to its effective blue-light strength or thermal strength. Table 2 from the text shows blue-light and thermal hazard coefficients at five nanometer intervals. In order to compute an effective blue-light or thermal strength, the measured spectral irradiance at these wavelengths is multiplied by the corresponding weights and summed across the spectral distribution to obtain an effective irradiation measure. These blue-light or thermal hazard measures are then compared with established limits for the ocular medium of concern (e.g., retina, lens).

For the band of radiation described in this report (.8 - 2 microns), our interest revolves around the thermal hazard function as the blue-light hazard in this spectral region is minimal. The thermal weights in this band (.8 - 2 microns) decrease monotonically with increases in wavelength. From Table 2, a conservative estimate for the thermal effects of radiation longer than .7 microns, then, is to simply use the thermal hazard weight associated with a wavelength of 700 nanometers (.7 microns) which has a value of one. Multiplying a weight of one by the spectral irradiance across the bands of interest and summing these products will yield the original measured irradiance or a maximum value of .55 mW/cm^2 as shown in Table 1.

The ACGIH (1981) provides several sources of comparison for this observed value. The first criterion is applicable to retinal burns for all infrared sources in the A (.7 - 1.4 microns) and B (1.4 - 3 microns) while a less conservative retinal burn standard exists for sources with no bright visible component, and a third standard exists for thermal damage to the lens. A value for each of these standards will be computed and compared with the effective irradiance given above of .55 mW/cm^2.

First, for any generalized source of ocular radiation in the infrared A (.7-1.4 microns) and B (1.4-3 microns) regions, the retinal burn upper limit is 10 mW/cm^2. The effective irradiation of .55 mW/cm^2 is well below this limit.

The less conservative criterion for retinal burns applies to sources without a bright visible component. Hartmann and Kleman (1980) introduced an estimate for this criterion. The ACGIH retinal burn infrared radiation exposure limit for broadband sources between 770 and 1400 microns where no bright visible components exist is:

$$L = .6 \times 10^3/\alpha = .8 \times 10^3 \times \Omega^{-.5} \text{ mW/(cm}^2 \text{ steradian)}$$

where α denotes the visual angle subtended by the source and $\Omega=\pi\alpha^2/4$ is the solid angle (for circular sources) subtended by

the source in three dimensions. As the visual angle or solid angle increases, the criterion above is lowered, indicating tighter bounds on the amount of irradiation allowed. We may choose to either neglect the visual angle and represent L in mW/cm^2, in which case L = 00 mW/cm^2, or incorporate α, the visual angle. Choosing an upper bound of 90 degrees or $\pi/2$ radians for the visual angle subtended by the radiation source, the resulting solid angle is approximately 1.94 steradians and

$$L = 488.5\ /(cm^2\ sr)$$

as a critical value for retinal irradiance. Dividing the largest irradiance from Table 1 (.55 mW/cm^2) by the solid angle of 1.94 steradians, the observed value would be .55/1.94 or .284 $mW/(cm^2\ sr)$. As expected, since the criterion L is a more liberal criterion than the general limit of 10 mW/cm^2, the observed value is approximately three orders of magnitude less than L, the criterion.

Thermal damage to the lens resulting in cataract formation also necessitates the formation of a criterion. Here, the assumption is made that lenticular damage will precede damage to the cornea due to the lens' inability to dissipate heat or repair itself. The ACGIH criterion for thermal damage to the lens injury is given as:

$$L' = 10/\Omega \quad mW/(cm^2\ sr).$$

Here again, we may choose to ignore the solid angle or use the solid angle of Ω=1.94 steradians computed above. For Ω=1.94 sr, L' = 5.15 $mW/(cm^2\ sr)$ and the observed value is .55/1.94 = .284 $mW/(cm^2\ sr)$. If we neglect the solid angle, we compare 10 mW/cm^2 with the effective irradiance from above of .55 mW/cm^2. In either case, the observed irradiance is substantially less than the criterion value.